Biodiversity Data Journal 14: e177882
doi: 10.3897/BDJ.14.e177882

Research Article

Predicting current and future distributions of bird species in South Africa's arid Northern Cape under climate change scenarios: are biomes being crossed?

Minoli Appalasamy‡, Fatima Parker-Allie§, Douglas M. Harebottle|

‡ Sol Plaatje University and South African National Biodiversity Institute, Kimberley, Cape Town, South Africa
§ South African National Biodiversity Institute, Cape Town, South Africa
| Sol Plaatje University, Kimberley, South Africa

Corresponding author: Minoli Appalasamy (m.appalasamy@sanbi.org.za)

Academic editor: Caio J. Carlos

Received: 12 Nov 2025 | Accepted: 09 Dec 2025 | Published: 20 Feb 2026

Citation: Appalasamy M, Parker-Allie F, Harebottle DM (2026) Predicting current and future distributions of bird species in South Africa's arid Northern Cape under climate change scenarios: are biomes being crossed? Biodiversity Data Journal 14: e177882. https://doi.org/10.3897/BDJ.14.e177882

Abstract

Climate change involves rising temperatures and altered precipitation patterns which lead to the contraction, expansion or shift in the ranges of biodiversity. This study employed MaxEnt to predict current and future distributions of three bird species native to South Africa and one invasive species. Future scenarios were modelled for 2050 and 2070 using three pathways: SSP1-2.6, SSP2-4.5 and SSP5-8.5 and four bioclimatic variables. The models showed good performance, with AUC values above 0.7, indicating high predictive accuracy. Comparisons between current ranges and future predictions show species, such as *P. purpureus* and *L. torquatus*, moving south-westwards and crossing into new biomes in response to changing climatic conditions. Meanwhile, *U. angolensis* shows drastic range contraction, with *A. tristis* showing expansion into arid environments. Across all concentration pathways, for both time periods, all species show expansion into southern arid regions of the Northern Cape. The models suggest that bird species are not only moving to different geographic areas, but are also likely to cross biome boundaries, which may have ecological implications. The study highlights how

© Appalasamy M et al. This is an open access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

climate change is a significant driver of changes in bird species distributions and their entry into new biomes. These findings underline the importance of adaptive conservation strategies that consider the dynamic nature of species distributions under climate change.

Keywords

biomes, birds, climate, distributions, MaxEnt, scenarios, South Africa, species distribution modelling

Introduction

Bird distributions are shifting due to environmental, biological, historical and human-induced factors (López-Ramírez et al. 2023). Climate is widely recognised as the main driver of large-scale changes across taxa (Márquez et al. 2011; Sun et al. 2020; Chamorro et al. 2021, López-Ramírez et al. 2023) and, for birds, shifts or expansions in range often follow changes in temperature, rainfall and habitat (López-Ramírez et al. 2023). Habitat alterations arise from bush encroachment (Kaphengst and Ward 2008), land degradation and transformation (Crick 2004) and climate change. Climate change can force species to track suitable conditions as climatic zones shift, leading to range reductions or fragmentation (Velásquez-Tibatá et al. 2012), with particular risk for narrow-range endemics (Manne and Pimme 2001). If species move into new habitats, these areas may be poorly protected or unsuitable (Araújo et al. 2004, Araújo et al. 2011).

Bush or shrub encroachment is a concern in savannah vegetation around the world and leads to changes in the structure of habitat diversity (Ward 2005, Kaphengst and Ward 2008). It has been reported that grazing, browsing, fire, climate and atmospheric carbon dioxide (CO_2) is causing woody encroachment into grassland and savannah vegetation (IPCC 2022). Bush encroachment is known to be severe in dry areas of the Northern Cape (Jordaan 2012). Bird species diversity (BSD) is positively related to structural habitat diversity whereby BSD increases with high structural diversity (a mixture of open grass areas and scattered trees, i.e. open savannahs) and decreases when structural diversity is low due to encroachment and fires (Kaphengst and Ward 2008, Lee et al. 2023). In arid areas, fires are less frequent due to low biomass (Brooks and Matchett 2006) and, in arid savannahs, there are tree species that are poorly adapted to cope with fires leading to their death (Lee et al. 2023). Tree loss in arid savannahs negatively impacts vertical habitat structure, eliminating shade, roosting and nesting sites and foraging resources. Studies show that bird communities respond strongly to changes in vegetation availability and structure (Seymour and Simmons 2008, Sirami et al. 2009, Seymour and Dean 2010, Ehlers Smith et al. 2015).

Forests support high bird diversity (Egwumah et al. 2018), but have declined due to human settlement, farming and fuelwood harvesting (Appalasamy et al. 2020, IPCC 2022). Climate-driven fire and rainfall shifts may further reduce forest extent (BirdLife

2018), threatening species reliant on tree habitats (Storch et al. 2003), such as the Green Wood Hoopoe (*Phoeniculus purpureus*) that depends on cavities (du Plessis 2010). Drought-linked tree mortality has caused 20% loss in parts of Africa between 1945 and 2007 (IPCC 2022). Habitat change alters food availability and range behaviour (Gregory et al. 2005), while degradation can promote alien bird establishment, impacting native species (Peacock et al. 2007).

Bird distribution in savannahs of southern Africa are affected by variables, such as soil type, rainfall and vegetation cover and structure (Lee et al. 2023). Studies have employed climatic variable 'envelopes', such as temperature and rainfall to predict current and future distribution shifts and patterns of species (Midgley et al. 2003, Simmons et al. 2004). With increased temperatures and decreased rainfall, predictions suggest shifts in several South African biomes, which will cause a shift in the distribution of endemic bird species (Simmons et al. 2004). According to Midgley et al. (2003), the bioclimatic envelope for arid Nama and Succulent Karoo biomes, which hold approximately 76% of south Africa's endemic birds (Siegfried 1992), is expected to undergo range reductions with south-eastward movements under mid-range climate change scenarios.

Several bird species in South Africa are expanding south-westwards into the Northern Cape, crossing biome boundaries. The Nama Karoo, which dominates this region, is arid with limited rainfall and is projected to experience higher temperatures, erratic rainfall and longer droughts, potentially leading to a shift towards savannah vegetation (Mukheibir and Sparks 2005, BirdLife 2018). These changing conditions may challenge colonising species, requiring adaptation to new environments. While SABAP data show range changes, detailed analyses of the drivers and potential for further expansion are lacking. This study investigates the impact of future climate scenarios on four expanding bird species in the Northern Cape, using species distribution models to predict their future extent of occurrence under forecasted climatic shifts.

Methods

Study area

The study area (Fig. 1) includes species occurrence data for all South African provinces, with a focus on the Northern Cape Province. South Africa offers a diverse and ecologically rich study area for investigating bird species distribution, encompassing a wide range of biomes (Mucina and Rutherford 2006). Its varied topography, climate zones and land-use patterns create distinct ecological niches that support both endemic and widespread bird species (Hockey et al. 2011). These environmental gradients make the region particularly valuable for understanding how habitat heterogeneity influences bird diversity and distribution.

Figure 1. doi

Map of study area, South Africa. Labels represent the various provinces: KZN: KwaZulu-Natal, EC: Eastern Cape, WC: Western Cape, NC: Northern Cape, FS: Free State, NW: North West, GT: Gauteng, MP: Mpumalanga, LIM: Limpopo.

Species of interest

The species selected for the study included: (a) *Phoeniculus purpureus* J.F. Miller (Green Woodhoopoe), (b) *Lybius torquatus* Dumont (Black-collared Barbet), (c) *Uraeginthus angolensis* Linnaeus (Blue Waxbill) and (d) *Acridotheres tristis* Linneaeus (Common Myna) (Fig. 2). *Phoeniculus purpureus* is widely distributed in sub-Saharan Africa, favouring mature woodland, riverine forest and savannah habitats. It forages communally for invertebrates in bark crevices and exhibits cooperative breeding behaviour, nesting in tree cavities and living in extended family groups (Ligon and Ligon 1990, Hockey 2005). *Lybius torquatus* occurs in forest edges, woodland and suburban gardens throughout eastern and southern Africa and primarily feeds on fruit (Hockey 2005). *Uraeginthus angolensis* is a small granivorous finch found across southern and central Africa in savannah, woodland and bushveld regions. It typically forages in pairs or small groups near water and adapts well to lightly disturbed or rural environments (Maclean 1993, Hockey 2005). The invasive *A. tristis* is native to South Asia and has rapidly expanded across urban and agricultural areas due to its omnivorous diet, tolerance of human-altered habitats and aggressive competition for nesting sites (Peacock et al. 2007, Grarock et al. 2012). These four species highlight different aspects of bird ecology, from cooperative behaviour and frugivory to granivory and invasive adaptability.

Primary species occurrences and data cleaning

Bird records were obtained from the Global Biodiversity Information Facility (GBIF). There were 126,011 records for *U.* (GBIF 2024a), 110,745 records for *P. purpureus* (GBIF 2024b), 178,843 records for *L. torquatus* (GBIF 2024c) and 161,838 records for *A. tristis* (

GBIF 2024d). For the native range of *A. tristis*, there were 2,134,462 records (GBIF 2025). Tools like Microsoft Access (for big data) and EmEditor were used to edit and remove columns.

Figure 2. doi

Species of interest: (a) *P. purpureus*; (b) *L. torquatus*; (c) *U. angolensis*; (d) *A. tristis*. Photo credits: Brian Culver.

Data cleaning was conducted in relation to variables like time, space and taxonomy (Chapman 2005, GBIF et al. 2010), while fields such as 'scientificName' were cleaned using the GBIF tool Species name matching (gbif.org). Here, species names were normalised from the .csv file against the GBIF Taxonomic Backbone. Spatial fields, like latitude and longitude, were verified using GIS Software which identified errors when data points were projected. Refraction was done to reduce sampling bias with the use of the 'Delete Identical' tool in the ArcGIS Pro Toolbox and retained records for modelling are as follows: *P. purpureus*: 9691 records, *L. torquatus*: 12,713 records, *U. angolensis*: 10,292 records and *A. tristis*: 11,754 records. The data format was adapted in EmEditor for use in MaxEnt.

Environmental variables

Bioclimatic variables for current scenarios were sourced from the WorldClim 2.1 database at a 2.5-minute spatial resolution. Future climatic data for CCSM4 Global Circulation Model (GCM) was sourced from WorldClim 1.4 – CMIP5 at a 2.5-minute spatial resolution. Data were downloaded for two time periods 2041-2060 (2050) and 2061-2080 (2070), using three Shared Socio-economic Pathways (SSPs); SSP1-2.6, SSP2-4.5 and SSP5-8.5. According to Sarkar and Talukdar (2023), SSPs represent future emission scenarios and are based on socioeconomic assumptions; whereby, SSP1-2.6 assumes a world focused on sustainability, leading to a projected temperature rise of ± 1.5–2°C by 2100, SSP2-4.5 assumes a world where socio-economic patterns continue

along historical trends, resulting in moderate emissions and a temperature increase of approximately 2.5–3°C by 2100 and SSP5-8.5 predicts a world where economic growth is driven by high energy consumption, relying strongly on fossil fuels, leading to a temperature rise exceeding 4°C by 2100. The emission scenarios data was downloaded as TIF. files and converted to ASCII files (.asc) using QGIS (version 3.4 Madeira software).

Modelling

Modelling was done using MaxEnt (version 3.4.1). The model was first run using all 19 bioclimatic variables with default settings applied. Thereafter, based on literature and Jackknife values, four bioclimatic variables were used in the final model: annual mean temperature, max temperature of warmest month, min temperature of coldest month and annual precipitation. These variables are ecologically meaningful for understanding the distribution and breeding ecology of the Common Myna. This species is also known for its ecological plasticity and adaptability (Pyšková et al. 2022). To account for pseudo-absence, background points (n = 10,000) were used and the following settings were applied: each model included 10 replicates for all species, auto feature class, regularisation multiplier was set at 1, with 70% of the species presence data used as training data and 30% as test data with Clog log output (complementary log-log [clog] transformation). Model performance was evaluated using the area under the receiver operating characteristic curve (AUC) which is a common measure of performance for SDMs (Amini Tehrani et al. 2021). Values with AUC > 0.7 were considered an indicator of good model performance in Maxent (Sarkar and Talukdar 2023). Additionally, True Skill Statistics (TSS) (Allouche et al. 2006) was used an additional indicator of model performance, with a range from −1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random. The following calculation was used TSS = Sensitivity + Specificity -1 whereby, Sensitivity (True Positive Rate) = TP/(TP+FN) and Specificity (True Negative Rate) = TN/(TN+FP). Threshold value used was the average maximum training sensitivity plus specificity Cloglog threshold.

Mapping

Maps were generated for each model as per Boral and Moktan (2021) using QGIS (version 3.4 Madeira software). The symbology for each species model was adjusted and colour bands ranged from 0 (low probability) to 1 (high probability).

Results

Important predictors and model performance

Based on Jackknife values, the bioclimatic variable which showed the greatest contribution to the model fits for all species was annual mean temperature (BIO1). The SDMs with AUC scores greater than 0.7 and TSS values of +1 had good performance in predicting the distribution of bird species. The AUC and TSS values were 0.79 and 0.85

(*L. torquatus*) and 0.81 and 0.96 (*P. purpureus*, *U. angolensis* and *A. tristis*), suggesting that the models have an excellent discriminative ability between presence and absence.

Current species distribution predictions

The predicted distribution (Fig. 3) showed all species to be present in parts of South Africa in accordance with species occurrence data. However, with all four species, there are outliers for the predicted distributional ranges. *Phoeniculus purpureus* (Fig. 3a) has a high number of outlying occurrence records in the Kgalagadi Transfrontier Park which is a fully protected national park and an important bird and biodiversity area (BirdLife 2018, Partnership 2025). The same applies for the species in the Western Cape; False Bay Nature Reserve and Boulders Beach. Fig. 4 shows the predicted distribution for the native occurrence dataset of *A. tristis*.

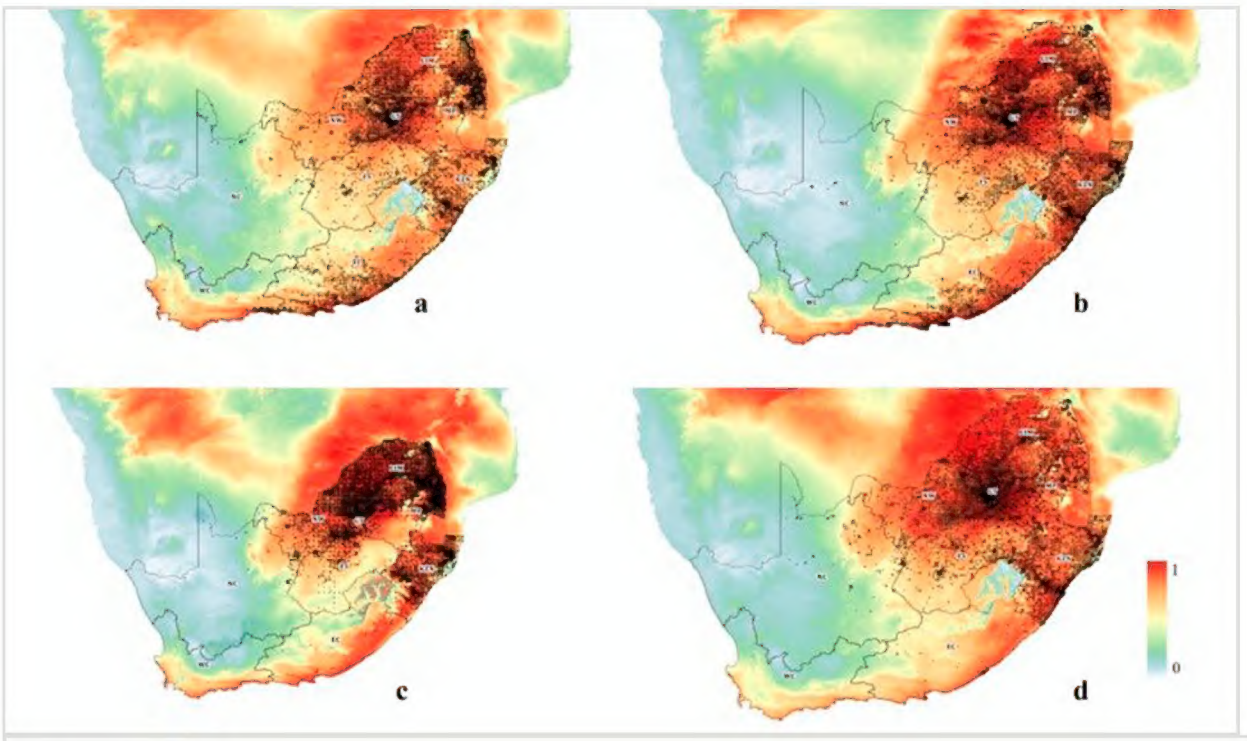

Figure 3. doi

Occurrence records (coloured dots) and predicted distributions (shaded) for (a) *P. purpureus*, (b) *L. torquatus*, (c) *U. angolensis* and (d) *A. tristis* in South Africa. The legend shading ranges from low probability (0) to high probability (1).

Future species distribution predictions

Under future climate change scenarios across two time periods, 2050 and 2070, the indigenous species (Figs 5, 6, 7) and the invasive species (Fig. 8) showed significant decreases in their distributional range. For all species and time periods, decreases in their distributional range was greatest for SSP5-8.5 (very high GHG emission). Between the two time periods, the greatest decrease in species distributional ranges is seen for 2070. Species trends show a south-westerly distributional range shift from current predicted ranges (Fig. 3) to future predictions (Figs 5, 6, 7, 8). There is a high probability that all species will enter southern to south-eastern parts of the Northern Cape, with

species like *U. angolensis* (Fig. 7) and *A. tristis* (Fig. 8) showing a higher presence compared to *P. purpureus* (Fig. 5) and *L. torquatus* (Fig. 6).

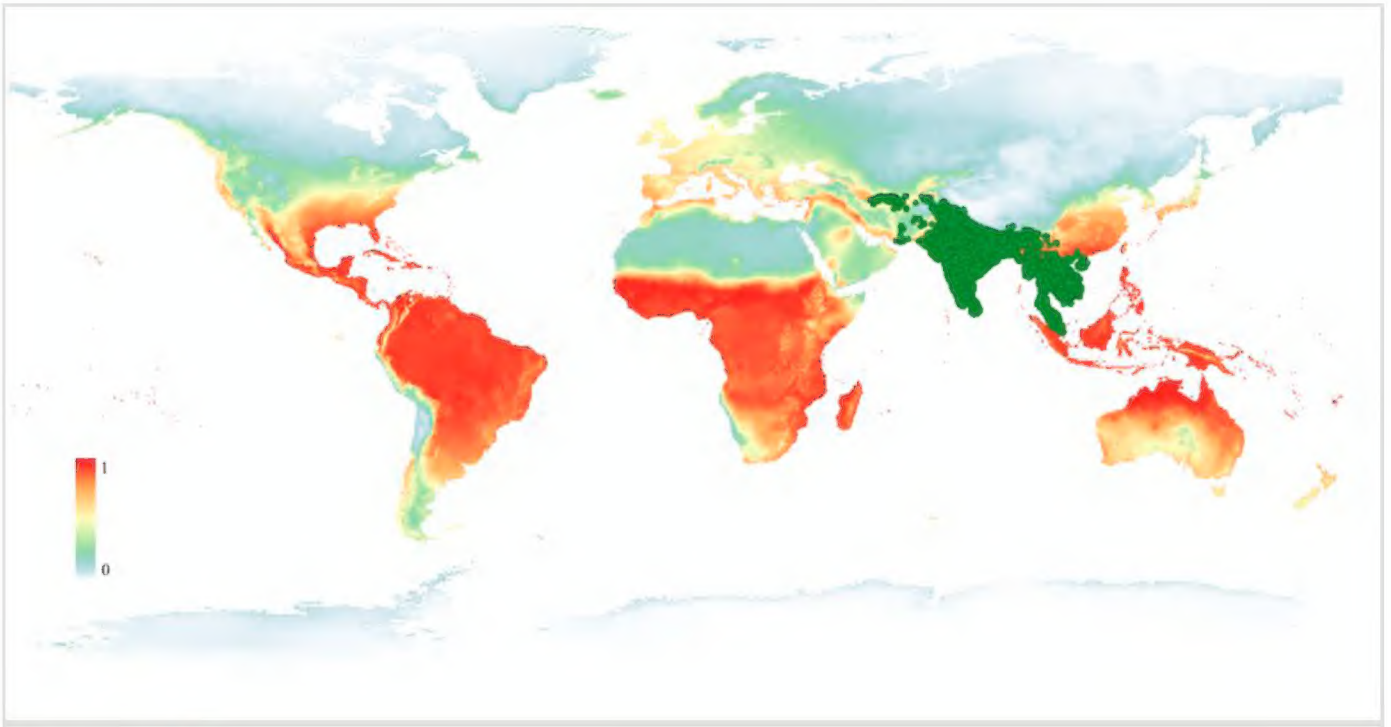

Figure 4. doi

Native range occurrence records (coloured dots) and predicted distribution (shaded) for *A. tristis*. The legend shading ranges from low probability (0) to high probability (1).

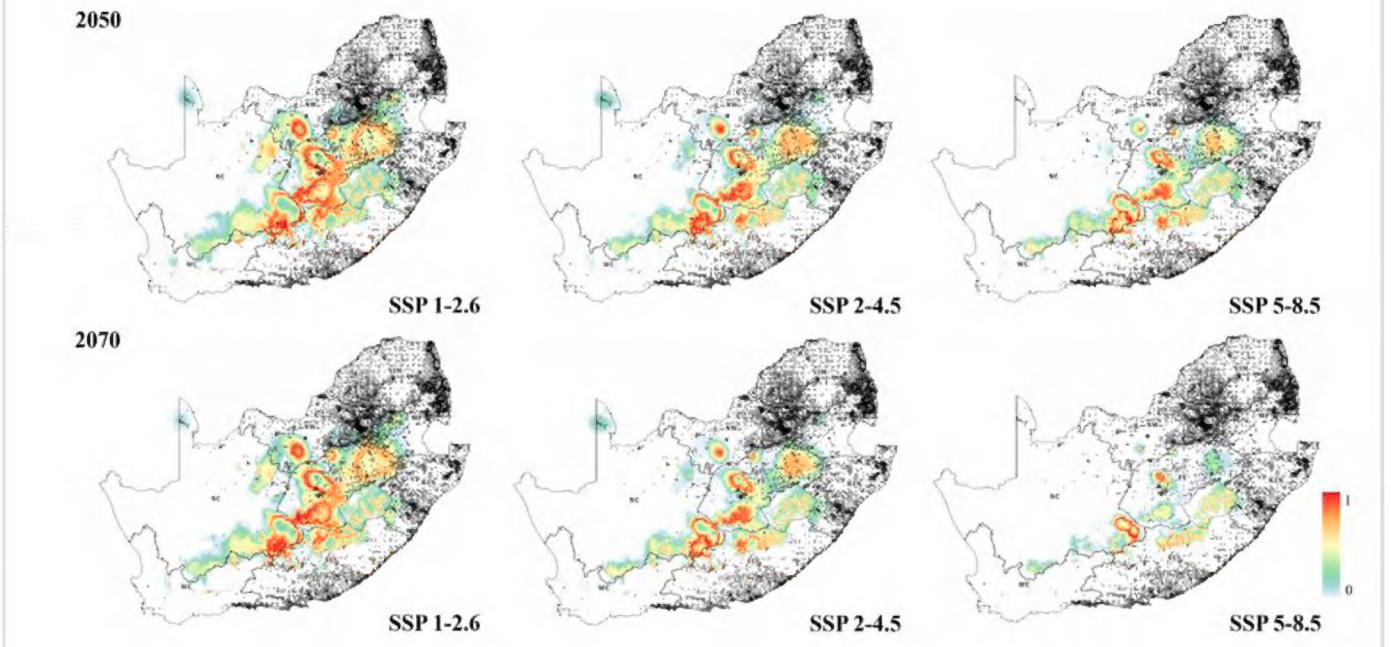

Figure 5. doi

Future prediction models for *P. purpureus* across two time periods; 2050 and 2070. Black dots indicate species occurrences.

When looking at trends for individual species across time periods and SSPs, patterns show an eastward shift in species distributional ranges, with all species ranges expanding into areas with higher elevations, such as the Free State (Maluti Mountains)

bordering Lesotho and northern parts of Eastern Cape (Drakensberg Mountains). Future predicted distributions of *P. purpureus* (Fig. 5) and *A. tristis* (Fig. 8) closely resembled one another compared to *L. torquatus* (Fig. 6) and *U. angolensis* (Fig. 7). A crossing of biome boundaries occurs for all species ranges from current predicted models (Fig. 3) to future predicted models under climate change scenarios, for both time periods (Figs 5, 6, 7, 8).

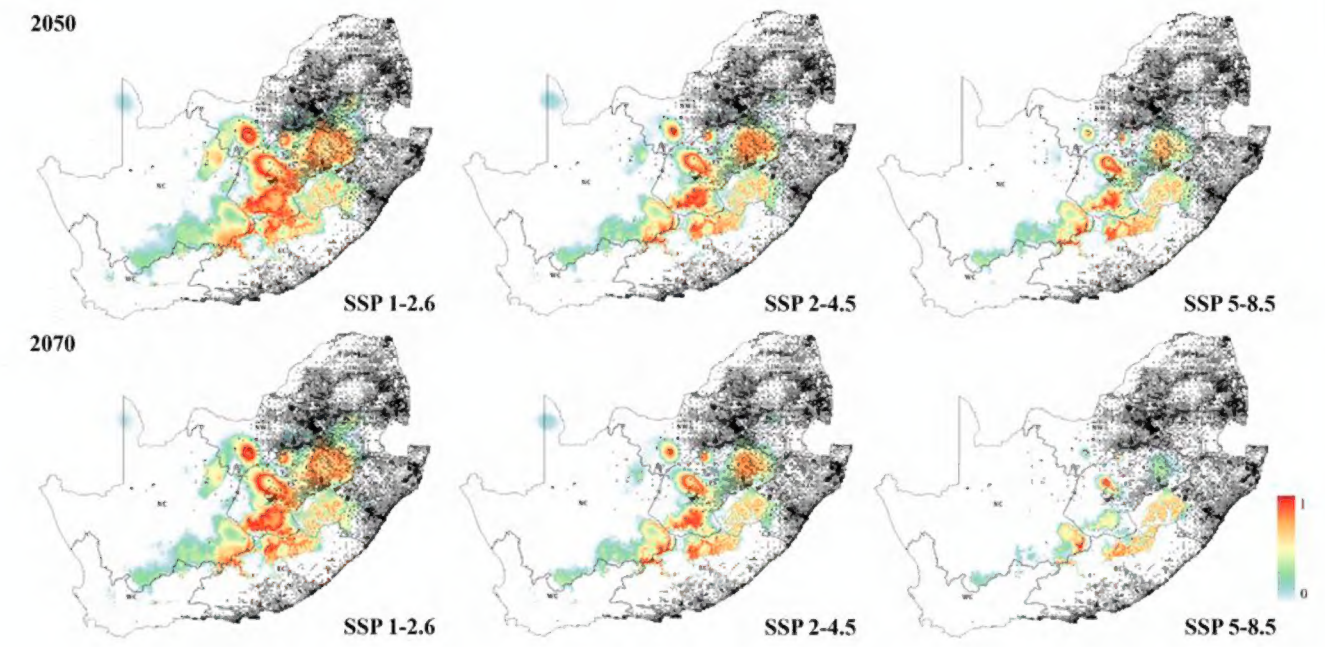

Figure 6. doi

Future prediction models for *L. torquatus* across two time periods; 2050 and 2070. Black dots indicate species occurrences.

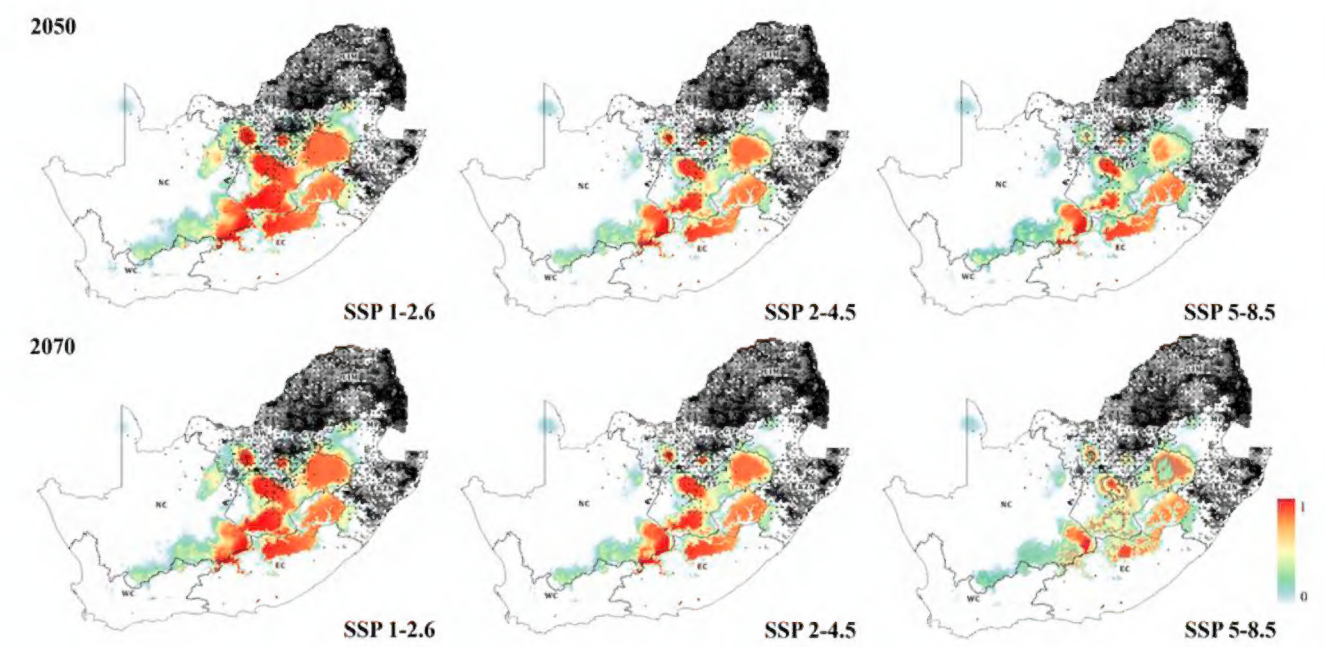

Figure 7. doi

Future prediction models for *U. angolensis* across two time periods; 2050 and 2070. Black dots indicate species occurrences.

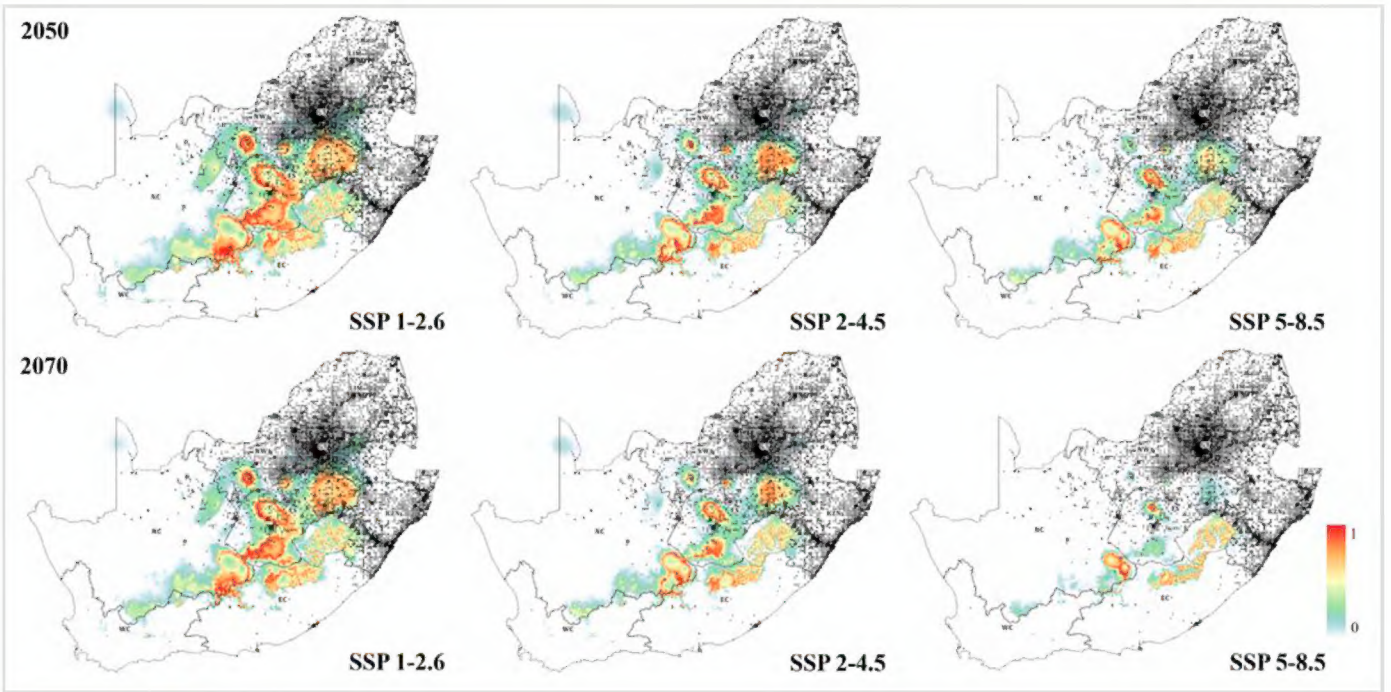

Figure 8. doi

Future invasive range prediction models for *A. tristis* across two time periods; 2050 and 2070. Black dots indicate species occurrences.

Models for *Acridotheres tristis* using invasive range occurrence data (Fig. 8) and native range occurrence data (Fig. 9) shows differences in the distribution of the species for the three SSPs over the two time periods. The future projections for the native occurrence dataset show this species to have a higher probability of extending into the south-western parts of the arid Northern Cape regions (Fig. 9) compared with the projected invasive distribution (Fig. 8). Additionally, there is also a higher probability of the Common Myna extending into higher lying areas, such as Lesotho and Free State, as well as parts of KZN and Mpumalanga when modelling the native occurrence dataset (Fig. 9).

Discussion

The observed range shifts of bird species in this study confirms our expectation of a south-westerly range shift of species into the arid Northern Cape. The main range shifts can be seen for all bird species under SSP1-2.6. Previous studies have indicated that land use change and climate change may have an effect on range shifts by South African bird species (either simultaneously or independently [Sirami et al. 2009, Hockey et al. 2011]) and authors infer that contractions in species ranges due to land-use change will cause species to be most affected by changes in climate, which can be seen by all bird species in this study. In contrast, other studies report that understanding the diet of different species helps to interpret its ranging behaviour in relation to food availability whereby distribution and abundance of bird species is determined by climate and availability of food resources (Gregory et al. 2005, Egwumah et al. 2018).

Phoeniculus purpureus is known to inhabit a variety of wooded environments with sufficient tree cover (Hockey 2005, du Plessis 2010). However, in future predicted models (Fig. 5), the species makes a shift in biomes from savannah to grassland and this may be

due to climate warming as well as shrub encroachment (Sirami et al. 2009). Range shifts and contractions are similar between *P. purpureus* and *L. torquatus* (Figs 5, 6) and are supported by reports (du Plessis 2010) stating these species have an overlap in the size of tree cavity entrances, showing their ability to share these cavities as roosting sites. It is important to note that woodhoopoes are unable to excavate these cavities themselves and, therefore, depend on birds of a similar size to do it for them (Radford and du Plessis 2004, du Plessis 2010). Furthermore, Radford and du Plessis (2004) suggest that roosting cavities can be used as a determining factor for the presence and survival of this species. The current predicted model for *P. purpureus* (Fig. 3a) shows the species to be present along the Eastern Cape coast, but over time and under climate change scenarios, they move inland.

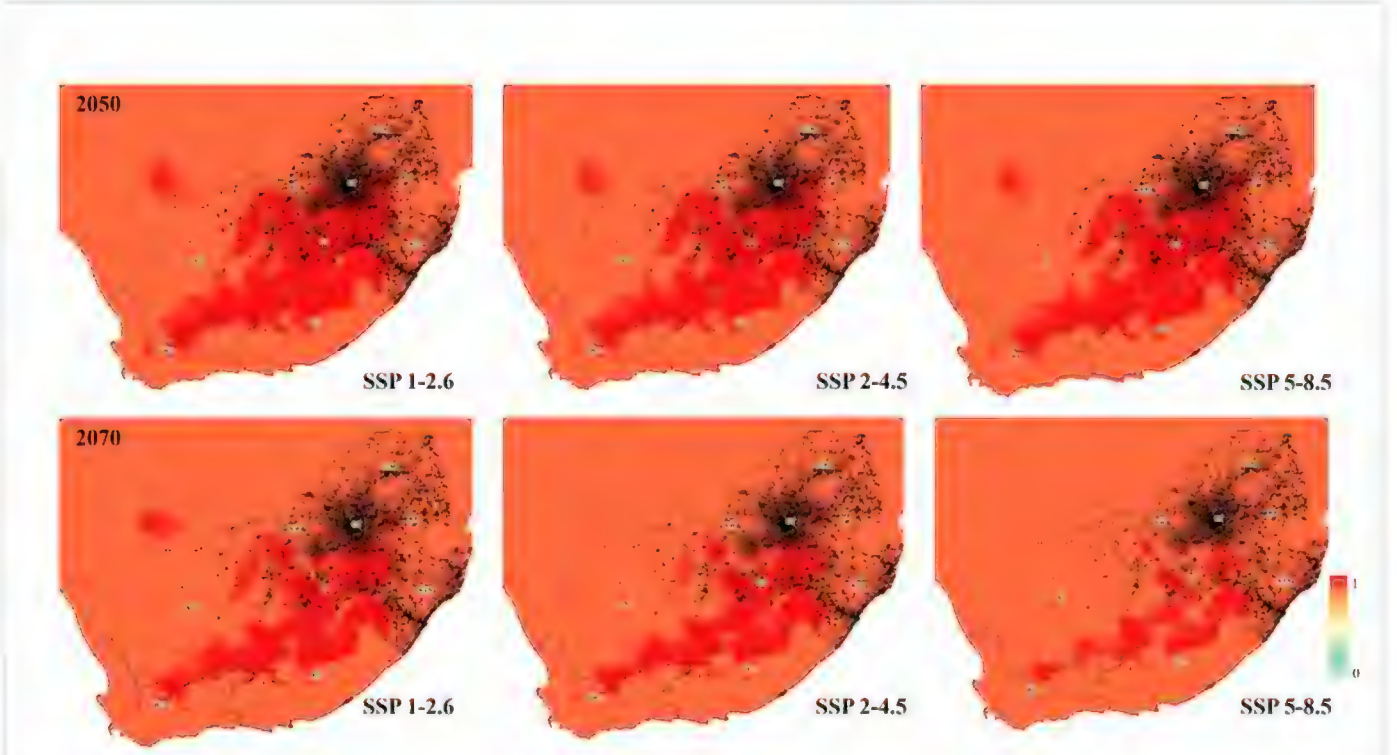

Figure 9. doi

Future native range prediction models for *A. tristis* across two time periods; 2050 and 2070. Black dots indicate species occurrences.

Phoeniculus purpureus (Bucerotiformes) and *U. angolensis* (Passeriformes) are recognised as southern African arid zone birds (Payne et al. 2023) and may find increasingly suitable habitats in the Northern Cape under future climate scenarios (Figs 5 , 7). The predicted increase in temperature and aridity in other parts of their range will make these regions more favourable, providing a refuge for these birds as their current habitats degrade. Payne et al. (2023) depict average spring-summer maximum temperatures to increase in the southern African arid zone, which includes the Western, Northern and Eastern Cape Provinces by 2050 under SSP2-4.5 and 8.5. Species shifts in the current study are consistent with global patterns where species are moving towards more arid regions as a response to warming climates (Huntley et al. 2016).

The current study shows *U. angolensis* undergoing drastic range contraction by 2050 and is entirely confined to high altitude regions, such as Lesotho under SSP5-8.5 (Fig. 7).

These results can be explained by outcomes of Payne et al. (2023) who found *U. angolensis* to be the most vulnerable bird order and the most vulnerable species with the highest sensitivity scores. Furthermore, this species was identified in 2020 during a mass mortality extreme heat event in eastern South Africa as vulnerable by making up 50% of songbird carcasses found (McKechnie et al. 2021b, Payne et al. 2023). Passerine vulnerability to extreme heat may be due to their reliance on panting, a means of evaporative heat dissipation, which is crucial for thermoregulation when air temperature exceeds body temperature (McKechnie et al. 2021). The blue waxbill is listed as a species of least concern in South Africa; however, this study and Payne et al. (2023) shows it to be of conservation concern due to its vulnerability to a changing climate.

Lybius torquatus, which requires cool and more stable climates, is expected to move to higher elevations in response to warming in lowland areas. The Drakensberg Mountains in Lesotho and the Eastern Cape Highlands offer cooler microclimates and refugia where these species can maintain their populations. The upward shifts are in line with global trends where montane species (butterflies) are migrating to higher altitudes to escape rising temperatures (Wilson et al. 2007). The shift to higher elevation is also seen with C3 grasses as their ranges contract (Parker-Allie et al. 2009).

Acridotheres tristis thrives in diverse environments, including urban areas, suggesting potential range expansion under all climate scenarios, especially SSP5-8.5 (Fig. 8), where environmental shifts may promote colonization. Such expansion could negatively affect native species through competition and predation, causing biodiversity loss (Pearson and Dawson 2003). Highly adaptable to extreme conditions, the Myna is extending its range in South Africa (Peacock et al. 2007), notably in the Northern Cape (Fig. 8), but remains limited in the Western Cape (Gumede and Downs 2019). Preventing spread into this province is crucial due to its wine industry, as the species favours sugary fruits (Baker and Moeed 1987, Gumede and Downs 2019). This fruit preference may drive its westward movement along the Orange River towards Upington, a major grape-growing area (Taljaard 2007, Raisins 2023). Even under SSP1-2.6, range expansion (Fig. 8) beyond current predicted areas is observed (Fig. 3d).

Distribution trends of the Myna support the findings of Khoury et al. (2021) who report that future distribution patterns are more associated with anthropogenic influences (e.g. human modified terrestrial lands) than climatic variables as reported by Orabi et al. (2024). Furthermore, the lack of this species in the Western Cape for future predictions align with global predictions (Magory Cohen et al. 2019). The scarcity of the Common Myna in these provinces links with earlier studies that discuss the introduction of this invasive species in South Africa (Peacock et al. 2007). The species' distribution overlaps with indigenous species, supporting evidence of competition for nesting sites, food and prey. This highlights the need to study factors driving its expansion into new areas, particularly the arid south-western Northern Cape.

Concluding Remarks

The study contributes to our understanding of the potential impacts of climate change on bird species distributions in South Africa, highlighting the possibility of biome transitions and the associated ecological risks. The findings underscore the need for continued monitoring of bird distribution changes in South Africa and adaptive conservation strategies to address the dynamic interactions between climate change, human activities and biodiversity.

Acknowledgements

We would like to thank SANBI-GBIF and the DSTI for the funding of this project and the GBIF Capacity Enhancement Support Programme, which enabled the collaboration with GBIF Spain, supporting a **Cross-continental partnership to investigate data mining approaches** and providing a foundation for this paper.

Hosting institution

Sol Plaatje University

Ethics and security

NA

Conflicts of interest

The authors have declared that no competing interests exist.

References

- Allouche O, Tsoar A, Kadmon R (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). Journal of Applied Ecology 43: 1223-1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x
- Amini Tehrani N, Naimi B, Jaboyedoff M (2021) Modeling current and future species distribution of breeding birds as regional essential biodiversity variables (SD EBVs): A bird perspective in Swiss Alps. Global Ecology and Conservation 27 https://doi.org/10.1016/j.gecco.2021.e01596
- Appalasamy M, Ramdhani S, Sershen (2020) Aliens in the city: Towards identifying non-indigenous floristic hotspots within an urban matrix. Flora: Morphology, Distribution, Functional Ecology of Plants 269 https://doi.org/10.1016/j.flora.2020.151631
- Araújo MB, Cabeza M, Thuiller W, Hannah L, Williams P (2004) Would climate change drive species out of reserves? An assessment of existing reserve-selection methods.

Global Change Biology 10 (9): 1618-1626. https://doi.org/10.1111/j.1365-2486.2004.00828.x

- Araújo MB, Alagador M, Cabeza M, Nogués-Bravo D, Thuiller W (2011) Climate change threatens European conservation areas. Ecology Letters 14 (5): 484-492. https://doi.org/10.1111/j.1461-0248.2011.01610.x
- Baker A, Moeed A (1987) Rapid genetic differentiation and founder effect in colonizing populations of Common Mynas (*Acridotheres tristis*). Evolution 41 (3): 525-538. https://doi.org/10.2307/2409254
- BirdLife (Ed.) (2018) The State of South Africa's Birds Report 2018. https://www.birdlife.org.za/media-and-resources/state-of-south-africas-bird-report/. Accessed on: 2024-6-18.
- Boral D, Moktan S (2021) Predictive distribution modeling of *Swertia bimaculata* in Darjeeling-Sikkim Eastern Himalaya using MaxEnt: current and future scenarios. Ecological Processes 10 (1). https://doi.org/10.1186/s13717-021-00294-5
- Brooks ML, Matchett J (2006) Spatial and temporal patterns of wildfires in the Mojave Desert, 1980-2004. Journal of Arid Environments 67: 148-164. https://doi.org/10.1016/j.jaridenv.2006.09.027
- Chamorro D, Martínez-Freiría F, Real R, Muñoz A (2021) Understanding parapatry: How do environment and competitive interactions shape Iberian vipers' distributions? Journal of Biogeography 48 (6): 1322-1335. https://doi.org/10.1111/jbi.14078
- Chapman A (2005) A guide to principles and methods of data cleaning for primary species and species-occurence data by Arthur Chapman. http://www.gbif.org/document/80528. Accessed on: 2024-5-13.
- Crick H (2004) The impact of climate change on birds. Ibis 146: 48-56. https://doi.org/10.1111/j.1474-919x.2004.00327.x
- du Plessis MA (2010) The influence of roost-cavity availability on flock size in the redbilled woodhoopoe *Phoeniculus purpureus*. Ostrich 60: 97-103. https://doi.org/10.1080/00306525.1989.9639624
- Egwumah PO, Ochepa C, Egwumah F (2018) Distribution, abundance and feeding behavior of Senegal Wood-Hoopes (*Phoeniculus purpureus*). In: Egwumah PO (Ed.) Proceedings of 2nd Wildlife Management Society of Nigeria Conference. Akure, September 2018.
- Ehlers Smith YC, Ehlers Smith D, Seymour C, Thébault E, van Veen F (2015) Response of avian diversity to habitat modification can be predicted from life-history traits and ecological attributes. Landscape Ecology 30 (7): 1225-1239. https://doi.org/10.1007/s10980-015-0172-x
- GBIF, Hill A, Ariño AH, Guralnick R (2010) GBIF position paper on future directions and recommendations for enhancing fitness-for-use across the GBIF network. GBIF URL: https://www.gbif.org/document/80623/gbif-position-paper-on-future-directions-and-recommendations-for-enhancing-fitness-for-use-across-the-gbif-network [ISBN 87-92020-11-9]
- GBIF (2024a) GBIF Occurrence Download. https://doi.org/10.15468/dl.q48mg3
- GBIF (2024b) GBIF Occurrence Download. https://doi.org/10.15468/dl.3tsbct
- GBIF (2024c) GBIF Occurrence Download. https://doi.org/10.15468/dl.k4mfn3
- GBIF (2024d) GBIF Occurrence Download. https://doi.org/10.15468/dl.946zf6
- GBIF (2025) GBIF Occurrence Download. https://doi.org/10.15468/dl.56bze5

- Grarock K, Tidemann CR, Wood J, Lindenmayer DB (2012) Is it benign or is it a pariah? Empirical evidence for the impact of the Common Myna (*Acridotheres tristis*) on Australian birds. PLos ONE 7 (7): e40622. https://doi.org/10.1371/journal.pone.0040622
- Gregory RD, van Strien A, Vorisek P, Meyling D, Noble R, Foppen D, Gibbons P (2005) Developing indicators for European birds. Philosophical Transactions of the Royal Society B: Biological Sciences 360 (1454): 269-288. https://doi.org/10.1098/rstb.2004.1602
- Gumede ST, Downs C (2019) Sugar preference of invasive Common Mynas (*Sturnus tristis*). Journal of Ornithology 160 (1): 71-78. https://doi.org/10.1007/s10336-018-1600-x
- Hockey PAR (2005) Burchell's courser. In: Hockey P, Dean W, Ryan P (Eds) Roberts– birds of Southern Africa. 7.
- Hockey PAR, Sirami C, Ridley A, Midgley G, Babiker H (2011) Interrogating recent range changes in South African birds: Confounding signals from land use and climate change present a challenge for attribution. Diversity and Distributions 17 (2): 254-261. https://doi.org/10.1111/j.1472-4642.2010.00741.x
- Huntley B, Collingham Y, Singarayer J, Valdes P, Barnard P, Midgley G, Altwegg R, Ohlemüller R (2016) Explaining patterns of avian diversity and endemicity: Climate and biomes of southern Africa over the last 140,000 years. Journal of Biogeography 43 (5): 874-886. https://doi.org/10.1111/jbi.12714
- IPCC (2022) Climate change 2022 – impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. https://doi.org/10.1017/9781009325844
- Jordaan A (2012) Drought risk reduction in the Northern Cape, South Africa. PhD Thesis
- Kaphengst T, Ward D (2008) Effects of habitat structure and shrub encroachment on bird species diversity in arid savanna in Northern Cape province, South Africa. Ostrich 79 (2): 133-140. https://doi.org/10.2989/OSTRICH.2008.79.2.2.576
- Khoury F, Saba M, Alshamlih M (2021) Anthropogenic not climatic correlates are the main drivers of expansion of non-native common myna *Acridotheres tristis* in Jordan. Management of Biological Invasions 12 (3): 640-653. https://doi.org/10.3391/MBI.2021.12.3.08
- Lee ATK, Herrmann E, Retief E, van der Westhuizen-Coetzer E, Seymour C (2023) The impact of a massive wildfire event on avian species richness and abundance in an arid African savanna ecosystem. Journal of Arid Environments 217: 105039. https://doi.org/10.1016/j.jaridenv.2023.105039
- Ligon JD, Ligon SH (1990) Green Woodhoopoes: life history traits and sociality. In: Stacey PB, Koenig WD (Eds) Cooperative breeding in birds: Long-term studies of ecology and behaviour. Cambridge University Press https://doi.org/10.1017/CBO9780511752452.003
- López-Ramírez S, Chamorro D, Real R, Muñoz A (2023) Southern Europe is becoming climatically favourable for African birds: anticipating the establishment of a new species. Frontiers in Zoology 20 (1). https://doi.org/10.1186/s12983-023-00496-x
- Maclean GL (1993) Roberts' Birds of Southern Africa. 6. John Voelcker Bird Book Fund. https://doi.org/10.1080/03768359308439693
- Magory Cohen T, McKinney M, Kark S, Dor R (2019) Global invasion in progress: modeling the past, current and potential global distribution of the Common Myna. Biological Invasions 21 (4): 1295-1309. https://doi.org/10.1007/s10530-018-1900-3

- Manne L, Pimme S (2001) Beyond eight forms of rarity: which species are threatened and which will be next? Animal Conservation 4 (3): 221-229. https://doi.org/10.1017/s1367943001001263
- Márquez AL, Real R, Olivero J, Estrada A (2011) Combining climate with other influential factors for modelling the impact of climate change on species distribution. Climatic Change 108 (1): 135-157. https://doi.org/10.1007/s10584-010-0010-8
- McKechnie AE, Gerson A, Wolf B (2021a) Thermoregulation in desert birds: scaling and phylogenetic variation in heat tolerance and evaporative cooling. Journal of Experimental Biology 224 (jeb229211). https://doi.org/10.1242/jeb.229211
- McKechnie AE, Rushworth I, Myburgh F, Cunningham S (2021b) Mortality among birds and bats during an extreme heat event in eastern South Africa. Austral Ecology 46 (4): 687-691. https://doi.org/10.1111/aec.13025
- Midgley M, Hannah F, Millar D, Thuiller W, Booth A (2003) Developing regional and species-level assessments of climate change impacts on biodiversity in the Cape Floristic Region. Biological Conservation 112: 87-97. https://doi.org/10.1016/S0006-3207(02)00414-7
- Mucina L, Rutherford M (2006) The vegetation of South Africa, Lesotho and Swaziland. 19. Strelitzia, South African National Biodiversity Institute, Pretoria.
- Mukheibir P, Sparks D (2005) Climate variability, climate change and water resource strategies for small municipalities. Report to the Water Research Commission. University of Cape Town. https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/1500-1-061.pdf
- Orabi G, Semida F, Medany D, Issa M, Ragab S, Kamel M (2024) Predicting the invasion range of the Common Myna, *Acridotheres tristis* Linnaeus, 1766 in Egypt under climate change. Sustainability 16 (15): 6495. https://doi.org/10.3390/su16156495
- Parker-Allie F, Musil C, Thuiller W (2009) Effects of climate warming on the distributions of invasive Eurasian annual grasses: a South African perspective. Climatic Change 94: 87-103. https://doi.org/10.1007/s10584-009-9549-7
- Partnership KBA (2025) Key biodiversity areas factsheet: Kgalagadi Transfrontier Park. Extracted from the world database of key biodiversity areas. https://keybiodiversityareas.org/
- Payne SL, Cunningham S, Howes C, McKechnie A (2023) A trait-based assessment of southern African arid-zone birds' vulnerability to climate change. Biological Conservation 287: 110338. https://doi.org/10.1016/j.biocon.2023.110338
- Peacock DS, van Rensburg B, Robertson M (2007) The distribution and spread of the invasive alien Common Myna, *Acridotheres tristis* L. (Aves: Sturnidae), in southern Africa. South African Journal of Science 103: 465-473.
- Pearson RG, Dawson T (2003) Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? Global Ecology and Biogeography 12 (5): 361-371. https://doi.org/10.1046/j.1466-822X.2003.00042.x
- Pyšková K, Pyšek P, Foxcroft L (2022) Introduction and invasion of common myna (*Acridotheres tristis*) in Kruger National Park, South Africa: still time for action? Biological Invasions 24: 2291-2300. https://doi.org/10.1007/s10530-022-02790-x
- Radford A, du Plessis M (2004) Green woodhoopoe *Phoeniculus purpureus* territories remain stable despite group-size fluctuations. Journal of Avian Biology 35 (3): 262-268. https://doi.org/10.1111/j.0908-8857.2004.03235.x

- Raisins R (2023) RedSun Raisin Report No. 9, South African Raisin Crop. https://redsun.co.za/reports/Redsun-Raisins-Report-9-2023.pdf
- Sarkar D, Talukdar G (2023) Predicting the impact of future climate changes and range-shifts of Indian hornbills (family: Bucerotidae). Ecological Informatics 74: 101987. https://doi.org/10.1016/j.ecoinf.2023.101987
- Seymour CL, Simmons S (2008) Can severely fragmented patches of riparian vegetation still be important for arid-land bird diversity? Journal of Arid Environments 72 (12): 2275-2281. https://doi.org/10.1016/j.jaridenv.2008.07.014
- Seymour CL, Dean W (2010) The influence of changes in habitat structure on the species composition of bird assemblages in the southern Kalahari. Austral Ecology 35 (5): 581-592. https://doi.org/10.1111/j.1442-9993.2009.02069.x
- Siegfried WR (1992) Conservation status of the South African endemic avifauna. South African Journal of Wildlife Research 22 (3): 61-64. URL: https://journals.co.za/doi/epdf/10.10520/EJC116903
- Simmons RE, Barnard P, Dean W, Midgley G, Thuiller W, Hughs G (2004) Climate change and birds: Perspectives and prospects from southern Africa. Ostrich 75 (4): 295-308. https://doi.org/10.2989/00306520409485458
- Sirami C, Seymour C, Midgley G, Barnard P (2009) The impact of shrub encroachment on savanna bird diversity from local to regional scale. Diversity and Distributions 15 (6): 948-957. https://doi.org/10.1111/j.1472-4642.2009.00612.x
- Storch D, Konvicka M, Benes J, Martinková J, Gaston K (2003) Distribution patterns in butterflies and birds of the Czech Republic: separating effects of habitat and geographical position. Journal of Biogeography 30 (8): 1195-1205. https://doi.org/10.1046/j.1365-2699.2003.00917.x
- Sun J, Qui H, Guo J, Xu X, Wu D, Zhong L, Jiang B, Jiao J, Yuan W, Huang Y, Shen A, Wang W (2020) Modeling the potential distribution of *Zelkova schneideriana* under different human activity intensities and climate change patterns in China. Global Ecology and Conservation 21: e00840. https://doi.org/10.1016/j.gecco.2019.e00840
- Taljaard PR (2007) The macro economy and irrigation agriculture in the Northern Cape Province of South Africa. Doctoral dissertation, University of the Free State
- Velásquez-Tibatá J, Salaman P, Graham C (2012) Effects of climate change on species distribution, community structure, and conservation of birds in protected areas in Colombia. Regional Environmental Change 13 (2): 235-248. https://doi.org/10.1007/s10113-012-0329-y
- Ward D (2005) Do we understand the causes of bush encroachment in African savannas? African Journal of Range and Forage Science 22 (2): 101-105. https://doi.org/10.2989/10220110509485867
- Wilson RJ, Gutiérrez D, Gutiérrez J, Monserrat V (2007) An elevational shift in butterfly species richness and composition accompanying recent climate change. Global Change Biology 13 (9): 1873-1887. https://doi.org/10.1111/j.1365-2486.2007.01418.x